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TECHNICAL REPORT

FUNDAMENTAL CHROMATICITY DIAGRAM WITH PHYSIOLOGICAL AXES – PART 1

CIE 170-1:2006

UDC: 612.84
535.66

Descriptor: Physiological optics, vision
Colorimetry

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3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
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FUNDAMENTAL CHROMATICITY DIAGRAM WITH PHYSIOLOGICAL AXES – PART 1

SUMMARY

CIE established, in 1991, the Technical Committee TC 1-36 with the following Terms of Reference: "Establish a fundamental chromaticity diagram of which the co-ordinates correspond to physiologically significant axes".

Part I of the report is limited to the choice of a set of colour matching functions and estimates of cone fundamentals for the normal observer, ranging in viewing angle from 1° to 10°.

The report starts with the choice of the 10° Colour Matching Functions (CMFs) of Stiles and Burch (1959). Then, following the ideas put forward by Stockman and Sharpe (2000), by application of König's hypothesis, and using the most modern data on the spectral sensitivity functions of dichromats, it is followed by the derivation of the spectral sensitivity functions of the long-wave sensitive (L-), medium-wave sensitive (M-) and short-wave sensitive (S-) cones, measured in the corneal plane for a 10° viewing field, the so called "cone fundamentals".

Next, by correcting these functions for the absorption of the ocular media and the macular pigment, and taking into account the optical densities of the cone visual pigments, all for a 10° viewing field, the low density absorbance functions of these pigments were derived.

Using these low density absorbance functions one can derive, taking the absorption of the ocular media and the macula, and taking into account the densities of the visual pigments for a 2° viewing field, the 2° cone fundamentals.

Using the same procedure one can derive cone fundamentals for every viewing angle between 1° and 10°.

Effects of age can also be incorporated by application of the relationship of the absorption of the lens as a function of age.

Tables are given, with intervals of 5 nm, of

- 10° cone fundamentals, both in terms of energy and quanta;
- optical density of the macular pigment;
- optical density of lens and other ocular media;
- the photopigment low density absorbance spectra;
- 2° cone fundamentals, both in terms of energy and quanta;
- maximal optical density of the macular pigment as a function of field size;
- the optical density of lens and other ocular media as a function of age;
- the maximal values of the optical density of the visual pigments as a function of field size.

DIAGRAMME FONDAMENTAL DE CHROMATICITE AVEC DES AXES PHYSIOLOGIQUES – PARTIE 1

RESUME

La CIE a établi, en 1991, le comité technique TC 1-36 de la Division 1 "Vision et couleur" avec le mandat suivant : "Etablir un diagramme fondamental de chromaticité dont les coordonnées correspondent à des axes physiologiquement significatifs". La partie I du rapport est limitée au choix d'un ensemble de fonctions colorimétriques et à l'évaluation des fondamentales de cônes pour l'observateur normal, pour un champ visuel allant de 1° à 10°.

Le rapport commence par le choix des fonctions colorimétriques 10° (CMFs) de Stiles et de Burch (1959). Puis, selon les idées proposées par Stockman et Sharpe (2000), en appliquant l'hypothèse de König et en s'appuyant sur les données les plus modernes des

fonctions de sensibilité spectrale des dichromates, on dérive les fonctions de sensibilité spectrale des cônes sensibles aux grandes (L), aux moyennes (M) et aux courtes (S) longueurs d'onde, mesurées dans le plan de la cornée pour un champ visuel de 10° , que l'on nomme "fondamentales de cônes" pour 10° .

Ensuite, en corrigeant ces fonctions de l'absorption des milieux oculaires et du pigment maculaire, et en tenant compte de la densité optique des pigments visuels des cônes, toutes valeurs établies pour un champ visuel de 10° , on dérive les fonctions d'absorbance spectrale relative pour une faible concentration de ces photopigments. A l'aide de ces fonctions d'absorbance spectrale relative pour une faible concentration de photopigment, on peut calculer, en tenant compte de l'absorption des milieux oculaires, du pigment maculaire, et de la densité optique des pigments visuels des cônes, toutes valeurs établies pour un champ visuel de 2° , les fondamentales de cônes pour 2° .

Par le même procédé, on peut dériver des fondamentales de cônes pour tout angle visuel entre 1° et 10° .

L'effet de l'âge peut également être incorporé en appliquant la relation de l'absorption du cristallin en fonction de l'âge.

Des tables donnent, avec un intervalle de 5 nm,

- les fonctions de sensibilité des fondamentales de cônes pour 10° , en termes d'énergie et de quanta;
- la densité optique du pigment maculaire;
- la densité optique du cristallin et autres milieux oculaires transparents;
- les spectres d'absorbance relative pour une faible concentration des photopigments;
- les fonctions de sensibilité des fondamentales de cônes pour 2° , en termes d'énergie et de quanta;
- la densité optique maximale du pigment maculaire en fonction du diamètre du champ visuel;
- la densité optique du cristallin et autres milieux oculaires transparents;
- la valeur maximale de la densité optique des pigments visuels en fonction du diamètre du champ visuel.

GRUNDLEGENDE FARBTAFEL MIT PHYSIOLOGISCHEN ACHSEN – TEIL 1

ZUSAMMENFASSUNG

Im Jahre 1991 richtete die Internationale Beleuchtungskommission (CIE) das technische Komitee TC 1-36 ein mit folgendem Auftrag: "Schaffung einer grundlegenden Farbtafel, deren Koordinaten physiologisch bedeutsamen Achsen entsprechen".

Teil I des vorliegenden Berichts beschränkt sich auf die Auswahl eines geeigneten Satzes von instrumentellen Spektralwertfunktionen und die Bereitstellung von spektralen Sehzapfen-Grundfunktionen für den Normalbeobachter, Funktionen, die für einen Sehwinkelbereich von 1° bis 10° gelten sollen.

Der Bericht beginnt mit der Wahl der 10° -Gesichtsfeld-Spektralwerte von Stiles und Burch (1959). Basierend auf den Ideen von Stockman und Sharpe (2000), werden die Königsche Hypothese, und die modernsten zahlenmäßigen Ergebnisse über die spektralen Empfindlichkeitsfunktionen der Dichromaten verwendet und die spektralen Empfindlichkeitsfunktionen der langwelligen (L), mittelwelligen (M) und kurzwelligen (S) Sehzapfen abgeleitet, präkorneal für ein 10° -Gesichtsfeld gemessen, die sogenannten "Sehzapfen-Grundfunktionen".

Danach werden aus diesen 10° -Gesichtsfeld-Grundfunktionen die spektralen inneren dekadische Extinktionswerte (die "spektrale Absorbanz") für verdünnte Sehzapfenpigment-Konzentrationen abgeleitet, indem - für ein 10° -Gesichtsfeld - die Absorption der okularen

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Medien und des Makulapigments berücksichtigt und die optische Dichte der Sehzapfenpigmente in Anrechnung gestellt wird. Mit Hilfe dieser "verdünnten" spektralen Absorbanz-Funktionen kann man 2°-Gesichtsfeld-Grundfunktionen nun dadurch herleiten, daß man für ein Gesichtsfeld sowohl die Absorption der okularen Medien und des Makulapigments als auch die optische Dichte der Sehzapfenpigmente berücksichtigt.

Nach dem gleichen Verfahren kann man Sehzapfen-Grundfunktionen für jeden Gesichtswinkel zwischen 1° und 10° ableiten.

Auch Auswirkungen des Lebensalters können durch die Beachtung der altersabhängigen Linsenabsorption einbezogen werden.

Es sind Tabellen angefügt, die in Intervallen von 5 nm u.a. folgendes erhalten:

- 10° Sehzapfen-Grundfunktionen, sowohl leistungs- als auch quantenflußbezogen;
- optische Dichte des Makulapigments;
- optische Dichte der Linse und der übrigen okularen Medien;
- Absorbanz-Spektren für Sehpigmente geringer Dichte;
- 2° Sehzapfen- Grundfunktionen, sowohl leistungs- als auch quantenflußbezogen;
- maximale optische Dichte des Makulapigments als Funktion der Gesichtsfeldgröße;
- optische Dichte der Linse und der übrigen okularen Medien als Funktion des Lebensalters;
- maximale Dichte-Werte der Sehpigmente als Funktion der Gesichtsfeldgröße.

1. INTRODUCTION

1.1 History

In 1931 CIE widened the scope of the photometric standard observer with the addition of colorimetric properties based on experimental studies by Wright (1928-1929) and by Guild (1931). Both of these studies were in terms of relative intensities, so that their final colour matching functions could only be defined after calibration with the photopic luminous efficiency function, $V(\lambda)$, which was established in 1924 by the CIE (CIE, 1926). This function had its problems though, because in the short wavelength region, the values were a compromise due to large differences between the results of various experiments. But even if the 1924 $V(\lambda)$ function had been faultless: this method presupposes a linear relation between photometry and colorimetry which needs not to be true and is not required to define colorimetric properties (Estévez, 1979).

A quarter of a century later Stiles and Burch determined a purely colorimetric database in a pilot study with ten observers (Stiles and Burch, 1955). The CIE, at its Zürich Session (CIE, 1955), did not consider the discrepancies between the CIE 1931 Standard Observer (CIE, 1931) and these 2° pilot data large enough to warrant a change in the standard data for practical colorimetry. Only a set of 10° colour-matching functions was derived to supplement the 2° existing colorimetric data basis (CIE, 1964).

However, vision researchers felt a need for an improved colorimetric observer as a common basis for their fundamental research. Other studies have since provided a great deal of additional information in terms of cone system action spectra. As there seems to be considerable convergence of ideas, it was appropriate to try to define a "Modified CIE Colorimetric Observer", in parallel to the Modified Photometric Observer, $V_M(\lambda)$, as published by the CIE (CIE, 1990). To that purpose CIE established, in 1991, the Technical Committee TC 1-36 with the following Terms of Reference: "Establish a fundamental chromaticity diagram of which the co-ordinates correspond to physiologically significant axes". The TC saw as its first task to "make the choice of a set of colour matching functions and estimates of cone fundamentals for the normal observer, ranging in viewing angle from 1° to 10°". Further it saw as its task to consider age as a variable.

This publication defines the 2° and the 10° Modified CIE Colorimetric Observers and provides guidance to calculate cone fundamentals for observers between 1° and 10° for different age groups. The report describes the underlying ideas, the methods, and the results, in terms of colour matching functions, receptor action spectra, photopigment action spectra for the eye media, etc. Colorimetric plots, one most similar to the CIE 1931 (x,y)-chromaticity diagram, in particular for those interested in its practical significance, and one in terms of cone system excitations, in particular for those interested in fundamental research, are also presented. All data were tabulated, with 5 nm spacing, and where necessary, in terms of both energy and quanta. All conclusions and recommendations are summarised in a final chapter, together with the prospects of further work.

1.2 Procedure

We call "cone fundamentals" the spectral sensitivity functions of the long-wave sensitive (L-), medium-wave sensitive (M-) and short-wave sensitive (S-) cones, measured in the corneal plane.

The derivation of cone fundamentals has a long history, starting with Helmholtz. Many attempts have been made since then. It should be recognised, however, that for deriving cone fundamentals from psycho-physical data, the committee is mainly influenced, as far as the way of data is concerned, by the work of Vos and Walraven (1971), by Smith and Pokorny (1975), by Stockman, MacLeod and Johnson (1993), and finally by Stockman, Sharpe and Fach (1999) and Stockman and Sharpe (2000).

The committee agreed to accept the derivation as described in the latter two papers, in which the findings of the other mentioned papers are incorporated, and to accept, with the exception of some details, their data as recommendation to be used for fundamental research

on colour vision. The committee agreed because it considers the choice of Stockman, Sharpe and Fach as:

- the best experimental database of colorimetric properties;
- the most reliable linear transformation of the colour matching functions $\bar{r}_{10}(\lambda)$, $\bar{g}_{10}(\lambda)$ and $\bar{b}_{10}(\lambda)$ to cone system action spectra $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$. Here König's interpretation of dichromacy as due to the complete loss of one cone system, is a necessary starting point, together with the current view that only the L- and M-systems notably contribute to luminance. Direct experimental action spectra, either from electrophysiological studies, or from psychophysical studies, or derived from dichromatic luminosity functions is considered as an additional evidence and a tool for validation rather than a primary input.
- the best modifying data of the intervening eye media on the spectra, so that the transformation from external (incident at the cornea) to internal (efficient for photopigment isomerisation) action spectra can be made;
- the way to bridge the gap between small-field and wide-field colorimetric properties by the thinning out of the macular pigment towards the periphery and by the subtle change in the action spectra due to a reduced effective optical density of the visual photopigments toward the periphery as appropriate.

Further:

- in the 10° case, the proposal by Stockmar and Sharpe to define the luminosity function, on quantum basis, as the addition of the appropriate proportions of $\bar{l}_{10}(\lambda)$ and $\bar{m}_{10}(\lambda)$ was followed, rather than take e.g. $\bar{y}_{10}(\lambda)$ of the CIE 1964 observer, which is not only based on the work of Stiles and Burch (1959), but mixed up with data of Speranskaya (1959);
- in the 2° case the proposal by Stockmar and Sharpe to define the luminosity function, on quantum basis, as the addition of the appropriate proportions of $\bar{l}(\lambda)$ and $\bar{m}(\lambda)$ was followed, rather than e.g. choosing $V(\lambda)$ of 1924 or $V_M(\lambda)$;
- agreement was sought on the best transformation to a system similar to CIE 1931 XYZ, and a proposal was formulated for a corresponding Fundamental Chromaticity Diagram. In line with the generally accepted null luminosity from the S-system, a Luther-MacLeod-Boynton diagram was constructed in terms of $S/(L+M)$ versus $L/(L+M)$ (Luther 1927, MacLeod, Boynton, 1979),
- finally, all data were tabulated, with 5 nm spacing, and where necessary, in terms of both energy and quanta. Tables with 1 nm and 0,1 nm spacing can be found on the Website <http://www.cvrl.ac.uk>.

1.3 Restrictions

Since observers, even within the same age bracket, may differ, a fundamental observer must be a theoretical construct based on averages. Any "real observer" will be different from the "Modified CIE Colorimetric Observer".

The starting functions are average colour-matching functions from a large sample (about 50 observers). An important inter-observer source of variability is the polymorphism of the photopigments, showing up in the small, probably hereditary, variations of a few nanometers in λ_{peak} of the cone fundamentals. Additional parameters such as the lens optical density, or macular pigment optical density, are given as average figures. Where relevant, the inter-observer variability will be dealt with as a separate remark at the appropriate chapter.

The relative spectral optical density of the macular pigment is assumed to remain the same at any eccentricity, although it is recognized that there exists a variability of the Lutein/Zeaxanthin (L/Z) ratio over the retina. It would not be surprising if the ratio would vary among observers, and that its distribution versus eccentricity would vary as well. Although the Lutein/Zeaxanthin (L/Z) ratio in the macular pigment changes with eccentricity on the

retina, the differences are considered not large enough to apply these for the calculations of the absorption by the macular pigment.

As a consequence of the inter-individual variations the accuracy of the tabulated values does not reflect actual accuracy. The number of decimals was chosen such that $[\Delta\text{Sensitivity}/\Delta\lambda]$ values can be safely used as representing differential quotients $[d\text{Sensitivity}/d\lambda]$ values in model calculations on for instance wavelength discrimination.

Finally, in order to keep this document manageable the committee has been rather restrictive in arguing our choices on literature data on spectral absorption and sensitivity. The detailed arguments should then be taken from the original publications. Whenever such a choice is made, it is marked as a recommendation and indicated in bold letters.

1.4 Structure of the report

The report contains three parts. After the general introduction (Chapter 1), which also includes a list of definitions and symbols, Part I, composed of Chapters 2 to 5, deals with the derivation of the cone fundamentals from the colour mixture functions and data tables in Chapter 6.

Chapter 2 deals with the derivation of the Modified CIE Colorimetric Observer for 10°. Chapter 3 is concerned with the derivation of the spectral absorbance functions of the three cone visual pigments. Chapter 4 deals with the derivation of the Modified CIE Colorimetric Observer for 2°.

Chapter 5 deals with the way a colorimetric observer can be derived for any field of view between 1° and 10° and for any age, from the Modified CIE Colorimetric Observer for 10°.

Chapter 6, finally, presents the tables pertaining to Part I.

Part II consists of chapters dealing respectively with the significance of the obtained results for photometry, and with the presentation of the results in terms of 2-dimensional chromaticity diagrams.

Part III consists of the summaries, the conclusions, and recommendations.

1.5 Definitions and symbols

Terms used in this report are defined according to the International Lighting Vocabulary (CIE, 1987).

The term cone fundamentals, however is not defined, and this committee recommends adding the following definition to the ILV:

cone fundamentals or fundamental colour-matching functions

spectral sensitivity functions of the long-wave sensitive (L-), medium-wave sensitive (M-), and short-wave sensitive (S-) cones, measured in the corneal plane

Symbols are respectively for spectral sensitivity functions:

$\bar{l}_{fs}(\lambda)$, $\bar{m}_{fs}(\lambda)$ and $\bar{s}_{fs}(\lambda)$ when expressed in terms of energy, and

$\bar{l}_{q,fs}(\lambda)$, $\bar{m}_{q,fs}(\lambda)$ and $\bar{s}_{q,fs}(\lambda)$ when expressed in terms of quanta,

"fs" indicating the field size.

Note 1. For the 2° data the "2" is usually omitted.

For example:

$\bar{l}(\lambda)$, $\bar{m}(\lambda)$ and $\bar{s}(\lambda)$ when expressed in terms of energy, and

$\bar{l}_q(\lambda)$, $\bar{m}_q(\lambda)$ and $\bar{s}_q(\lambda)$ when expressed in terms of quanta for a 2° field size; and

$\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ when expressed in terms of energy, and

$\bar{l}_{q,10}(\lambda)$, $\bar{m}_{q,10}(\lambda)$ and $\bar{s}_{q,10}(\lambda)$ when expressed in terms of quanta for a 10° field size.

Note 2. The functions are usually presented normalized such that the maximum value of each is unity.

Note 3. It is recommended that the terms cone fundamentals or fundamental colour-matching functions are used to specify the spectral sensitivity functions measured in the corneal plane. The use of the terms "fundamentals" or "fundamental response curves" is advised against, because these terms are sometimes used in other meanings.

2. CONE FUNDAMENTALS FOR THE 10° OBSERVER

2.1 Task definition

We call as "cone fundamentals" the spectral sensitivity functions of the long-wave sensitive (L-), medium-wave sensitive (M-) and short-wave sensitive (S-) cones, measured in the corneal plane. The cone fundamentals are a linear transformation of the colour-matching functions (CMFs) of the observer.

The task in this chapter, the derivation of the cone fundamentals for the young adult 10° field size observer, means the definition of the parameters in the following equations:

$$\begin{aligned}\bar{l}_{10}(\lambda) &= l_R \cdot \bar{r}_{10}(\lambda) + l_G \cdot \bar{g}_{10}(\lambda) + l_B \cdot \bar{b}_{10}(\lambda) \\ \bar{m}_{10}(\lambda) &= m_R \cdot \bar{r}_{10}(\lambda) + m_G \cdot \bar{g}_{10}(\lambda) + m_B \cdot \bar{b}_{10}(\lambda) \\ \bar{s}_{10}(\lambda) &= s_R \cdot \bar{r}_{10}(\lambda) + s_G \cdot \bar{g}_{10}(\lambda) + s_B \cdot \bar{b}_{10}(\lambda)\end{aligned}\quad (2.1)$$

in which $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ are the cone fundamentals, $\bar{r}_{10}(\lambda)$, $\bar{g}_{10}(\lambda)$, $\bar{b}_{10}(\lambda)$ the colour-matching functions both at corneal level, and $l_R, \dots, s_B$ the relevant coefficients.

Since we are interested only in relative values – we will normalise all cone fundamentals to peak height one – it is only the ratio $l_R : l_G : l_B$, etc. which matters.

2.2 Basic assumptions

2.2.1 The colour matching functions (CMFs)

After a careful examination of the colour-matching data, the recommendation by Stockman and Sharpe (2000) has been followed to adopt the choice of the large field 10° CMFs of Stiles and Burch (1959), based upon matching data using mixtures of 645,2 nm (R), 526,3 nm (G), and 444,4 nm (B). It constitutes the most comprehensive set of CMF-data, which were measured directly, by a large number of subjects (49 subjects from wavenumber 25 500 cm⁻¹ to 14 000 cm⁻¹, and by 9 subjects from wavenumber 15 000 cm⁻¹ to 12 133 cm⁻¹), were not contaminated by photometric adjustment, and have not been modified by other CIE committees (see Table 6.1). However, the values of $\bar{b}_{10}(\lambda)$ beyond 505 nm show such a large spread, that they (see Fig 2.1) should be disregarded. The values beyond 505 nm are derived from other psychophysical data, (see Section 2.3.2).

It is recommended to use as the colour-matching data for the 10° visual field the 10° CMFs of Stiles and Burch (1959), excluding the values of $\bar{b}_{10}(\lambda)$ beyond 505 nm. (See Table 6.1 in terms of energy, and Fig. 2.1.)

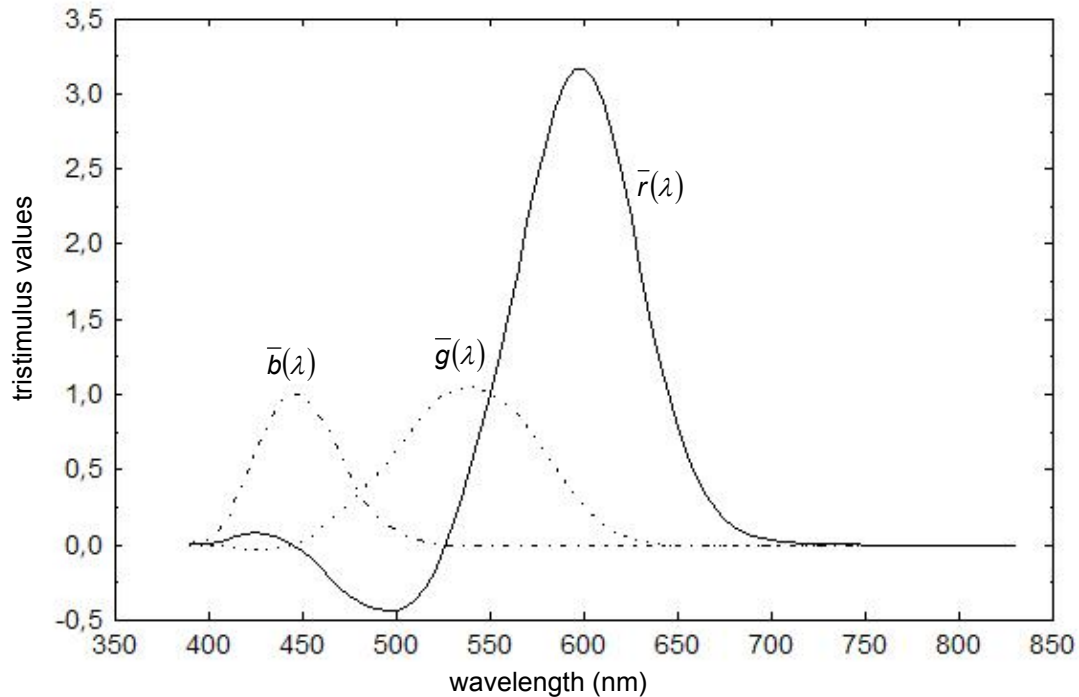


Fig. 2.1. The Stiles-Burch colour matching functions.

2.2.2 The König hypothesis

The theoretical basis for deriving cone fundamentals is the König hypothesis, which postulates that dichromatic vision is a reduced form of trichromatic vision where one cone system is missing and the two others are left unchanged in spectral sensitivity. This hypothesis has been confirmed many times since, both by retinal densitometry (Rushton, 1964; Rushton, Powell and White, 1973) and on the basis of psychophysical arguments (Vos and Walraven, 1971).

Consequently, the cone fundamentals should reflect the spectral sensitivity of the visual system measured in the case of

- dichromacy;
- foveal tritanopia;
- cone response isolation.

Several estimates have been constructed from CIE standard observer colour matching functions. Every attempt has contributed to an improved prediction of the cone fundamentals.

Stockman and Sharpe (2000) used all three methods, and came to a proposal, which reflects present knowledge.

The mentioned basic assumptions are further elaborated in Section 2.3.

2.3 The 10° cone fundamentals

2.3.1 L_{10° and M_{10° -cone fundamentals, and the S_{10° -cone fundamental from 390 nm to 505 nm

If we are concerned only about the relative cone spectral sensitivity, the transformations for

$\bar{l}_{10}(\lambda)$ and $\bar{m}_{10}(\lambda)$ simplify to:

$$(l_R / l_B) \cdot \bar{r}_{10}(\lambda) + (l_G / l_B) \cdot \bar{g}_{10}(\lambda) + \bar{b}_{10}(\lambda) = k_l \cdot \bar{l}_{10}(\lambda) \quad (2.2)$$

$$(m_R / m_B) \cdot \bar{r}_{10}(\lambda) + (m_G / m_B) \cdot \bar{g}_{10}(\lambda) + \bar{b}_{10}(\lambda) = k_l \cdot \bar{m}_{10}(\lambda) \quad (2.3)$$

where k_l and k_m are scaling constants.

According to Stockman and Sharpe (2000) the following numerical data hold:

$$2,846201 \cdot \bar{r}_{10}(\lambda) + 11,092490 \cdot \bar{g}_{10}(\lambda) + \bar{b}_{10}(\lambda) = k_l \cdot \bar{l}_{10}(\lambda) \quad (2.4)$$

$$0,168926 \cdot \bar{r}_{10}(\lambda) + 8,265895 \cdot \bar{g}_{10}(\lambda) + \bar{b}_{10}(\lambda) = k_m \cdot \bar{m}_{10}(\lambda) \quad (2.5)$$

Where the S-cones are virtually insensitive to long-wavelength light, s_R is taken to be zero. This leads to

$$(\bar{s}_R / \bar{s}_B) \cdot \bar{g}_{10}(\lambda) + \bar{b}_{10}(\lambda) = k_s \cdot \bar{s}_{10}(\lambda) \quad (2.6)$$

in which k_s is a scaling constant.

According to Stockman and Sharpe (2000) the following numerical data hold for the wavelength region 390 nm to 505 nm.

$$0,0106 \cdot \bar{g}_{10}(\lambda) + \bar{b}_{10}(\lambda) = k_s \cdot \bar{s}_{10}(\lambda) \quad (2.7)$$

2.3.2 S_{10} -cone fundamental beyond 505 nm

Due to the poor accuracy of the $\bar{b}_{10}(\lambda)$ -values for wavelengths beyond 505 nm, a better estimation for deriving the $\bar{s}_{10}(\lambda)$ is obtained indirectly from other psychophysical experiments (Stockman and Sharpe, 2000). A Gaussian expansion (see Chapter 4) is used to fit the experimental results collected on a 2° field (Stockman, Sharpe and Fach, 1999) and readjusted back to 10° , using the same assumptions as those described in Chapter 4.

2.3.3 L_{10} -, M_{10} - and S_{10} -cone fundamentals

It is recommended to use the following formulas for transformation from CMFs to the L_{10} -, M_{10} - and S_{10} -cone fundamentals (the latter only in the wavelength region of 390 nm to 505 nm), normalised to 1 at the maximum values (see Tables 6.2 and 6.3).

$$\begin{aligned} \bar{l}_{10}(\lambda) &= 0,192325269 \cdot \bar{r}_{10}(\lambda) + 0,749548882 \cdot \bar{g}_{10}(\lambda) + 0,0675726702 \cdot \bar{b}_{10}(\lambda) \\ \bar{m}_{10}(\lambda) &= 0,0192290085 \cdot \bar{r}_{10}(\lambda) + 0,940908496 \cdot \bar{g}_{10}(\lambda) + 0,113830196 \cdot \bar{b}_{10}(\lambda) \\ \bar{s}_{10}(\lambda) &= 0,0105107859 \cdot \bar{g}_{10}(\lambda) + 0,991427669 \cdot \bar{b}_{10}(\lambda) \quad (390 \text{ nm to } 505 \text{ nm region}) \end{aligned} \quad (2.8)$$

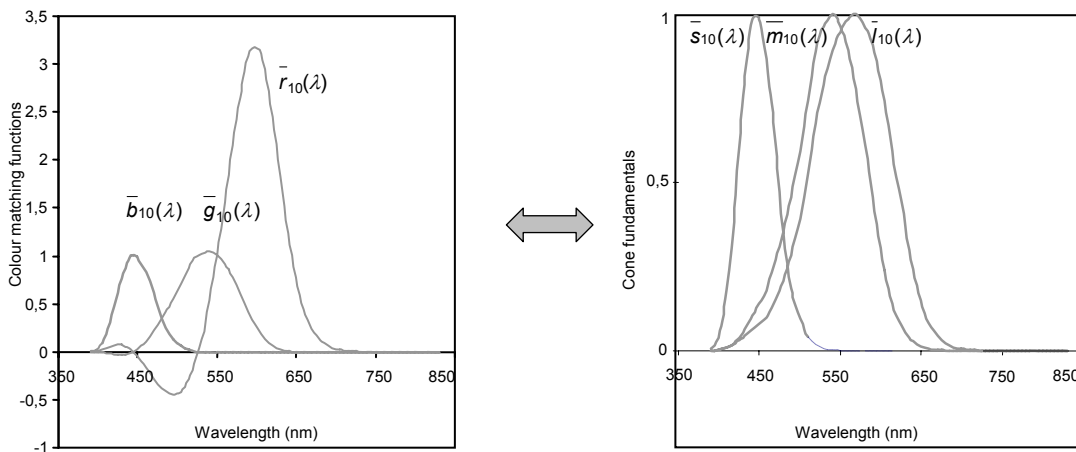


Fig. 2.2. Illustration of the transformation from colour matching functions to cone fundamentals in terms of energy. The transformation is carried out by using Eq. 2.8.

Only the values of $\bar{s}_{10}(\lambda)$ up to 505 nm are derived this way.

For the wavelength region beyond 505 nm this course is complemented by the tabulated values given in Tables 6.2 and 6.3. These values are derived from the Gaussian expansion of the 2° data as given in Chapter 4.

2.3.4 Transformation of cone fundamentals in terms of energy to cone fundamentals in terms of quanta.

The 10° L-, M-, and S-cone fundamentals in terms of energy $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ are given in Table 6.2.

To convert the 10° L-, M-, and S-cone fundamentals in terms of energy $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$ to cone fundamentals in terms of quanta, respectively $\bar{l}_{q,10}(\lambda)$, $\bar{m}_{q,10}(\lambda)$ and $\bar{s}_{q,10}(\lambda)$, one should multiply values presented in Table 6.2 by $1/\lambda$. Doing so, the maximum values are no longer equal to one, and should therefore be re-normalized to one. This re-normalisation has to take place as close to the maximum values as possible, but anyhow as close as allowed in a table with 0,1 nm as wavelength interval. Results are given in Table 6.3.

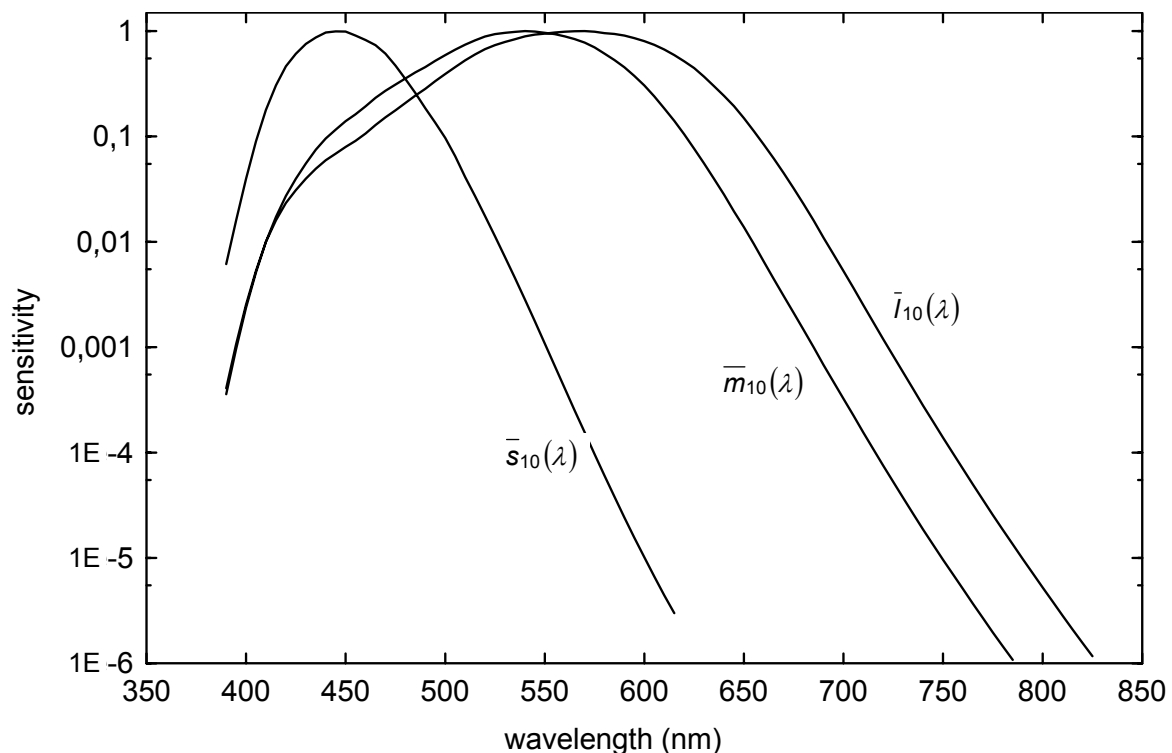


Fig. 2.3. The 10° L-,M-, and S-cone fundamentals in terms of energy $\bar{l}_{10}(\lambda)$, $\bar{m}_{10}(\lambda)$ and $\bar{s}_{10}(\lambda)$, normalised to 1 at the maximum, as given in Table 6.2.

3. DERIVATION OF THE PHOTOPIGMENT ABSORPTION SPECTRA

3.1 Task definition

In Chapter 2 the 10° cone fundamentals, as the most reliable basic set of data, were derived. In order to derive compatible cone fundamentals for other field sizes, from 1° to 10°, it is necessary to make an intermediate step via the photopigment absorption spectra. That requires knowledge of the spectral absorption characteristics of the intermediate inert pigments in the ocular media.

It is therefore necessary to know:

- the absorption spectrum by the macular pigment;
- the absorption spectrum by the lens and other pre-retinal media.